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# RESEARCH AND DEVELOPMENT OF AN ADVANCED PERSONAL LOAD CARRIAGE SYSTEM PHASES II AND III

## Section A: Further Developments of Comprehensive Measurement Systems

by

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# Further Developments of
# Comprehensive Load Carriage Measurement Systems


Executive Summary

Under DCIEM contract #W7711-5-7273/001/TOS, numerous improvements were made to the equipment and protocol for load carriage system testing in the APLCS project These improvements focused on three areas :

## 1. Measurement Systems

**Ground Reaction Forces and Moments** - incorporation of load cell at torso hip level
**Contact Pressure** - measurement from four pressure sites with addition of second F-Scan system
**Strap Forces** - improved transducer attachment method, increased number of gauges
**Relative Motion** - source firmly attached on mannikin, improved software developed.
**Data Management Software** - data collection and display improvements made to software

## 2. Physical Systems

**Pneumatic Control System** - valves and software improved for better control, increase in programmable motions.
**Anthropometric Model Torsos** - four mannikins created to compare results across sizes and genders

## 3. Test Protocol Changes

**Stiffness Testing** - improved testing jig, data collection automated
**Component Testing** - mannikin created for component testing, custom shoulder straps developed
**Portable Testing** - preliminary trials conducted of simultaneous quantitative data collection in field

The nature of these improvements, along with an explanation of their incorporation into the current LCS testing protocol, are further explained in the following section Recommendations for future test development work, focussing on the portable system, are also included

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# Further Developments of
# Comprehensive Load Carriage Measurement System

## 1.0 Introduction

The experimental progress of contract #W7711-5-7273/001/TOS saw several significant changes made to the tests and equipment previously developed by the Ergonomics Research Group under contract # W7711-4-7225/01-XSE The purpose of these changes was to increase the rate and ability of the evaluation testing to measure the performance of different LCS, and to quantify the performance impact of additional clothing or gear a soldier might be required to carry Testing improvements also made it possible to more accurately measure LCS design characteristics during dynamic testing, over a wider range of body sizes Changes to existing equipment were directed at increasing the test sensitivity to the measured variables, increasing the number of test variables recorded, improving test protocols, and streamlining data acquisition and reduction. To this end, post-processing software was developed to collate relative displacement, reaction force, reaction moment, and strap force data, and increase the sped and ease of report generation Improvements to tests and equipment are described in the following section on load carriage testing enhancements.

Additions to the group of test and evaluation tools, such as the LC system stiffness tester and the LC system component tester, were aimed at increasing the ability to accurately quantify the effect of design changes. Preliminary work was also done to demonstrate a technique by which quantitative LC system evaluation, including dynamic measurements of surface contact pressures and strap force tensions, could be conducted outside the laboratory setting, in active field trials In addition to the potential for testing LC Systems under realistic use conditions, a portable field measurement system can provide valuable benchmark data for laboratory tests These initiatives are also described in the following sections.

# 2.0 Load Carriage Simulator Enhancements

The load carriage simulator (LC Sim) consisted of an instrumented rigid torso mounted on a displacement programmable platform The platform was supported by three air cylinders which provide vertical motion while allowing rotation about the x and y axes The pneumatic drive system was programmed to perform two repeatable displacement functions a regular sinusoid to represent walking; and a series of motions about 3 axes to represent an obstacle avoidance manoeuver During LC Sim testing, load control and load transfer characteristics of LC systems were measured A full protocol for LC Sim testing can be found in Annex A 1.

## 2.1 Measurement Systems - Ground Reaction Forces and Moments

The amount of force required at the hip level during load carriage, to maintain balance, is of interest for LC system testing because the generation of this excess muscle force is related to increased soldier fatigue In LC system testing under contract #W7711-5-7273/001/TOS , LC Sim torso models were mounted on a 6 degree-of-freedom load cell (AMTI Incorporated) such that the neutral axis of the load cell was coincident with the transverse axis of rotation of the torso hip joint This load cell was used in LC system test setup to balance the reaction moments at the mannikin's hip in preparation for dynamic testing This balancing of the hip reaction moments ensured that the LC Sim torso, with LC system in place, had adopted a forward body lean that would require minimal counterbalancing forces LC users in the field have been found to assume a similar forward lean, in an effort to minimize the muscular effort required for balance (Stevenson et al , 1995) In dynamic assessments, the load cell is used to assess hip joint reaction forces and moments and associations between these values and the muscular effort associated with carriage of that system can be drawn

## 2.2 Pneumatic Control System - Hardware and Software for Extended Motions

Improved control of the displacement pneumatics was required to maintain repeatability of test parameters (displacement, frequency) across the range of body weights and equipment combinations that were to be tested For example, the mass of the 95$^{th}$ percentile mannikin, with standard LC system payload and necessary test equipment, totaled greater than 120 kg. Also, control improvements were necessary to repeatedly perform newly programmed LC Sim motions, namely jogging and lateral slip To increase the robustness and repeatability of the LC Sim, the control valves and software were upgraded under contract #W7711-5-7273/001/TOS The original control valves, a simple open/shut style, were replaced with proportional control valves (Festo Incorporated), allowing the LC Sim control computer software to monitor and vary the differential pressure across each cylinder face The original LC Sim control software was replaced with a second generation that used a PDP (pressure - delta pressure) algorithm to improve the repeatability of the displacement function

## 2.3 Anthropometric Model Torsos

Size variations and anatomical differences, both within a gender and across genders, can create fit problems, resulting in reduced comfort and capability, when considering the design of a LC system or fighting order kit. This concern drove the major improvement made to the LC Sim testing during contract #W7711-5-7273/001/TOS, which was the development of a family of four anthropometric mannikins. These mannikins, as described in Table 2 3 and seen in Figure 2 3, were dimensioned to be representative of the following human sizes· a 5$^{th}$ percentile female, a 50$^{th}$ percentile female; a 50$^{th}$ percentile male; and a 95$^{th}$ percentile male as described by the Safework™ human modeling system. Anthropometric data for critical mannikin dimensions was supplied by the 1988 US Army ANSUR anthropometric database Each mannikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks

Production of the mannikins was performed by Morgese-Soriano Limited to these custom specifications The human models consisted of a fibreglass outer shell with an expandable poured polyurethane foam filling Proper mass distribution was achieved by thoroughly mixing aggregate with the interior foam A vertical cylindrical cavity was created in each mannikin to allow for mounting of a 6 degree-of-freedom load cell In each case, the neutral axis of the load cell was positioned at the approximate location of the mannikin's hips This load cell was further mounted on a single axis articulating vice, which permitted the mannikin and LC system to be placed in a balanced anterior body lean position for load carriage Finally, the surface of each mannikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used on prosthetics, to approximate the compressive response of human skin over bone For all tests, the mannikin was dressed in a Canadian Forces standard issue combat shirt

**Table 2.3.** Summary of Mannikin Anthropometric Data

| Anthropometric Measurement | Female | | | | Male | | | |
|---|---|---|---|---|---|---|---|---|
| | 5 th Percentile | | 50 th Percentile | | 50 th Percentile | | 95 th Percentile | |
| | Model[1] | Mannikin | Model[1] | Mannikin | Model[1] | Mannikin | Model[1] | Mannikin |
| neck circumference (cm) | 31.4 | 28.8 | 34.8 | 34.4 | 40.8 | 39.5 | 43.2 | 45.7 |
| acromial height sitting (cm) | 52.1 | 59.2 | 55.6 | 61.0 | 59.8 | 61.5 | 63.4 | 67.5 |
| chest circumference, maximum (cm) | 76.7 | 83.8 | 90.7 | 91.4 | 99.1 | 101.6 | 107.8 | 107.6 |
| chest circumference, armpit (cm) | 76.2 | 78.2 | 88.7 | 85.5 | 102.3 | 101.2 | 110.7 | 106.8 |
| waist circumference, navel (cm) | 63.6 | 65.1 | 79.2 | 79.2 | 86.2 | 84.5 | 96.6 | 99.8 |
| biacromial breadth (cm) | 33.6 | 33.3 | 36.3 | 35.4 | 39.7 | 38.0 | 41.6 | 40.5 |
| back length, C7 to L4/L5 (cm) | 46.3 | 47.1 | 48.9 | 48.2 | 50.6 | 45.3 | 53.7 | 52.1 |
| buttock circumference (cm) | 80.6 | 85.0 | 96.7 | 100.5 | 98.4 | 95.4 | 107.2 | 109.5 |
| weight (N) , adjusted to reflect upper 20% of limbs | 271 | 276 | 350 | (4) | 444 | 476 | 546 | (4) |

1 Model data was generated by the Safework™ Program

2 Back length data for all models was calculated as follows:

Back length (cm) = sitting height - menton to top of head - (waist height-buttock height)

3. Weight data for all models was calculated as follows:

Weight (N) = weight (head/neck) + weight (upper arms) + weight (upper trunk) + weight (mid trunk) + weight (lower trunk)

Weight (N) = $weight_{total}$ (9.6%) + $weight_{total}$ (6.6%) + $weight_{total}$ (18.5%) + $weight_{total}$ (12.2%) + $weight_{total}$ (10.7%)

4 Not available

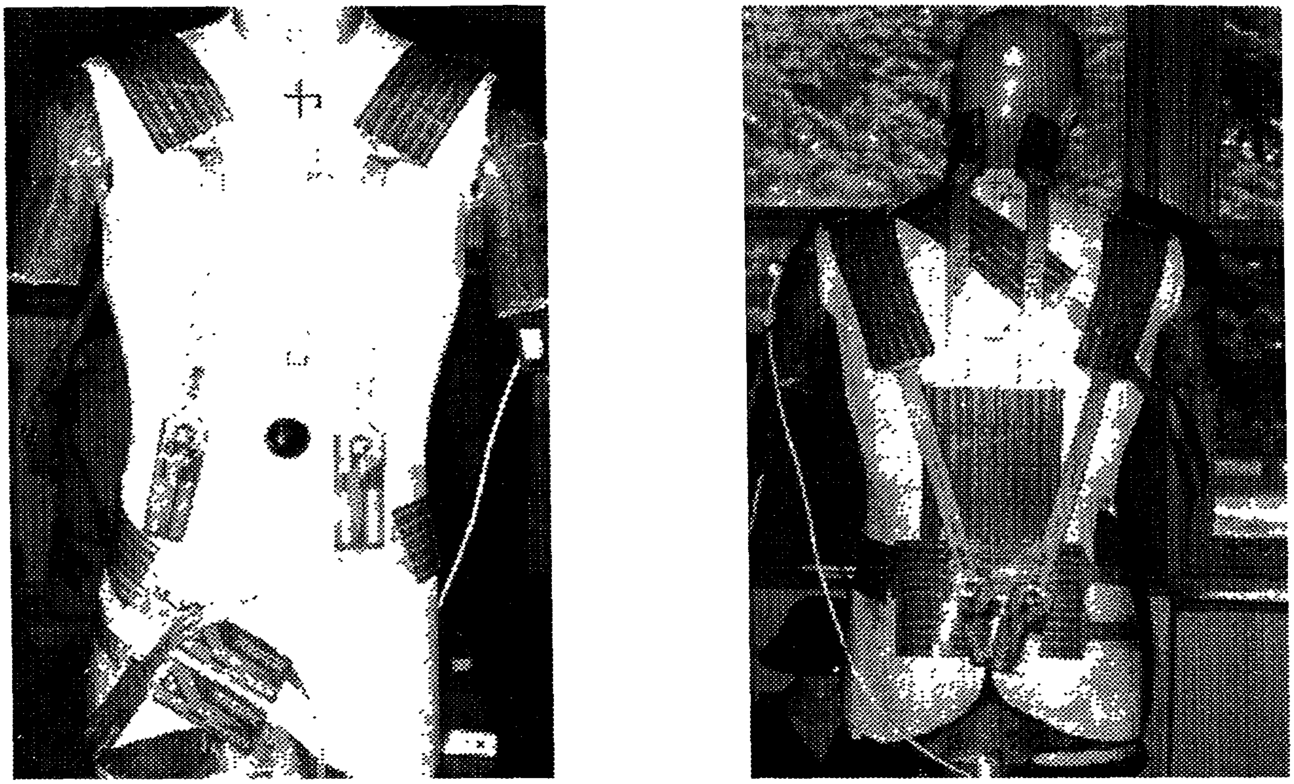

**Figure 2.3** Anterior and posterior views of $50^{th}$ %ile male mannikin, with F-Scan™ sensors in place

## 2.4 Measurement Systems - Contact Pressure

An F-Scan™ pressure sensor system (Tekscan Incorporated) was used in the LC Sim testing to acquire contact pressure data on the mannikin surface This technology measures the change in resistance across a thin layer of ink, which is deformed when pressure is applied This ink layer is contained between two plastic sheets. The sensors used in this study (F-Scan™ type 9810/1924/C/75/50) were 76 mm x 206 mm x 0 2 mm thick and had 96 active sites Previous testing at Queen's (DCIEM Contract #W7711-4-7225/01-XSE) has found the F-Scan system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results.

Simultaneous collection of pressure data from four sensor locations was made possible through the addition of a second F-Scan™ system (computer card, two data transfer cuffs with cables), under contract #W7711-5-7273/001/TOS This enhanced capability allowed for pressure measurements in two additional anatomically significant sites, the scapular area and the upper lumbar region A Hewlett-Packard 660 II Colour Printer was also combined with the LC Sim computer control network to allow for the generation of full colour pressure plots

### Other Measurement Systems - Strap Forces

For all LC system testing, the force in the waist and shoulder straps were measured using custom designed full bridge axial load cells New strain transducers of identical design were produced under contract #W7711-5-7273/001/TOS to facilitate field testing of LC systems Improvements were also made to the strain transducer data collection software, and a more effective method of attaching the transducers in-line with the LC system suspension components was developed

### Other Measurement Systems - Relative Motion

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional relative displacement data, with displacement measured between the LC system and the user. For the testing of contract #W7711-5-7273/001/TOS, the electromagnetic field source for the Fastrak™ was attached to the ceiling of the laboratory, directly over the LC Sim Fastrak™ sensors were also attached in a secure position to the superior polystyrene surface of the LC System payload and to the mannikin Displacement data, for the payload with respect to the source, was recorded for 10 seconds at 55 Hz every 300 seconds over the duration of the test Enhancements to the Fastrak™ data collection software allowed for improved data storage, as well as built in displacement vector resolution

## 2.5 Data Management Software

Special purpose software programs were written to assist with management of the relative displacement, load cell, and strap force data The program BPAccel automatically records 18 seconds of displacement data, with a sampling rate of 55 hz, at 10, 300, 600, 900, and 1200 seconds of elapsed testing time. Load cell and strap force data are sampled at the same frequency and time intervals by control software created with a Viewdac™ (Keithley-Asyst) system. Output files from these software packages were then passed to automated postprocessing software, which allows for automatic generation of summary plots and tables

# 3.0 LC System Testing Enhancements

Subsequent to the development of LC Sim testing, further static tests were developed to isolate specific LC system design features. These include LC system frame stiffness testing, which was initially conducted under contract #W7711-4-7225/01-XSE and was largely improved under contract #W7711-5-7273/001/TOS, and LC system component testing This work, which to date has focused on shoulder strap shapes and styles, as well as the validity of the F-Scan™ pressure measurement system in shoulder modeling, has been developed through the work of Master's level and undergraduate students. New work investigating the effect of LCS suspension design changes, and improved methods of pressure system calibration is also ongoing.

A method of making of relative pack/person displacement, strap tension, and contact pressures during dynamic human factors testing of LC systems

## 3.1 LC System Stiffness Testing

The purpose of this study was to perform stiffness testing on a selection of military packs with different clothing configurations to evaluate the resistance to rotational motion normally expected during walking or marching Previous studies have indicated that restriction of this normal motion increases the metabolic cost of gait by 10 % during moderate walking Furthermore, torsional compliance is necessary to assure free relative motion between the shoulders and hips during agility activities A pack stiffness tester was developed to evaluate the performance of each pack configuration in three independent modes of rotational motion (forward bending, sideways bending, and torsional twisting).

### 3 1.1 Apparatus

A pack stiffness test jig (Figure 3.1-1.) was developed to allow the placement of each load carriage system onto a two-piece anatomical human trunk model (50 percentile male) The model was custom-fitted with a layer of compliant synthetic skin, 5.0 mm thick Bocklite™ The upper torso portion of the model was free to rotate about a horizontal axis (y-axis for forward bending or x-axis for sideways bending) on two oil impregnated metal powder sintered bearings at the L3/L4 location of the human spine, or about the vertical axis (z-axis for torsional twisting) on a thrust bearing at the L4/L5 location. Only one degree of freedom was active for each type of tests, with the other degrees of freedom mechanically locked The lower waist portion of the model was rigidly fixed in an upright standing position to the steel support frame

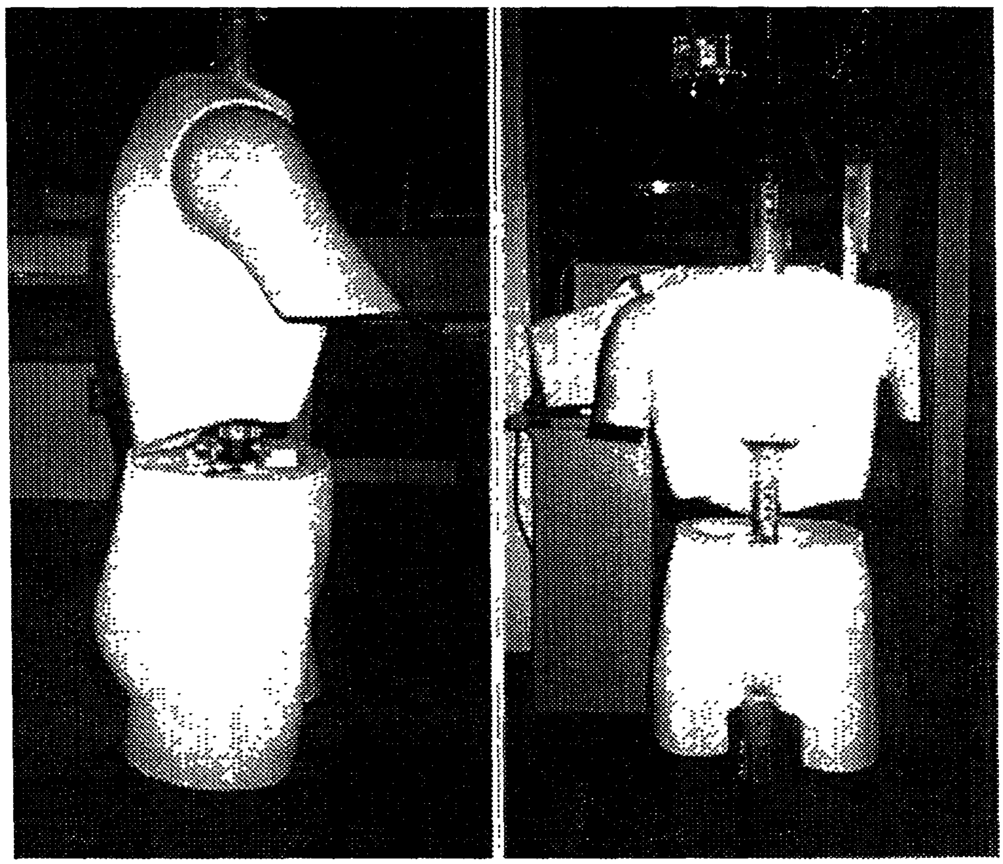

**Figure 3.1-1. Pack Stiffness Testing Apparatus**

The anatomical trunk model allowed relative rotation of the upper torso with respect to the lower portion about each of the three axes Cutouts were necessary on the upper torso to facilitate gap closure during tests The configuration shown was setup for the sideways bending tests, (A) lateral and (B) frontal views The model was custom-fitted with a layer of compliant synthetic skin

### 3.1.2 Protocol

Empty load carriage systems were used in this test to generate baseline LC system stiffness values, without the increased pack stiffness due to kit items. Each pack was placed in position on the model and all straps were securely fastened Using in-line force transducers, the shoulder straps and the hip/waist strap were pre-tensioned to 55 N and 40 N respectively, the same settings were used in the load carriage simulator tests.

During each test run, analog signals from the two load cells and two potentiometers were captured using a data acquisition system (Keithley MetraByte Instruments Incorporated) in a portable personal computer at a sampling rate of 5Hz over a three minute period Each data set was saved electronically on the hard drive for post-processing A spreadsheet was used to post-process the data, with each data set partitioned into the first cycle and repeated cycles Only the loading phase of each test cycle was analyzed. Load cell data was filtered first by averaging over a one or two degree intervals of rotation and further averaged over two to four repeated test runs . For the forward and sideways bending tests, the upper torso displayed an apparent resistance against the bending motions. Baseline reference tests were established for the setup (upper torso without pack or clothing equipment) and a baseline correction was applied to the data sets by subtraction For the torsional twisting tests, upper torso response had an insignificant effect on the torque transducer output and the baseline correction was not applied The information was reduced to bending moments or torque about the hinge in Nm and relative rotation in degrees to produce characteristic moment-rotation curves for each pack configuration. Linear regressions were performed on each LC system data set to obtain an aggregate pack stiffness (slope of linear regression)

*Lateral Bendıng Stiffness*

Load/moment was applied in the form of a horizontal force acting on a moment arm of 0 93m This was achieved by means of two opposing cables attached to an overhead load transfer assembly (LTA) mounted on a roller track (Figure 3.1-2). Each cable was pre-tensioned by a 5 kg mass to maintain proper alignment A custom made in-line tension transducer, similar to those used in the measurement of strap forces during LC simulator testing, was installed between the loading cable and the LTA to measure cable tension fluctuations during each load cycle. A modified trailer winch (Fulton Performance Products Incorporated) fitted with a multi-turn precision potentiometer was used to induce and measure the horizontal displacement of the LTA. Maximum excursion of the LTA was 1 04 m resulting in a forward bending angle of 48 degrees For the sideways bending tests, the anatomical trunk model was rotated 90 degrees about the base while keeping the bearing assembly in its original orientation with respect to the LTA. Excursion of the LTA was reduced to 0 31 m resulting in a sideways bending angle of 18 degrees. The normal range expected during walking/marching gait was about 2-7 degrees about the neutral axis

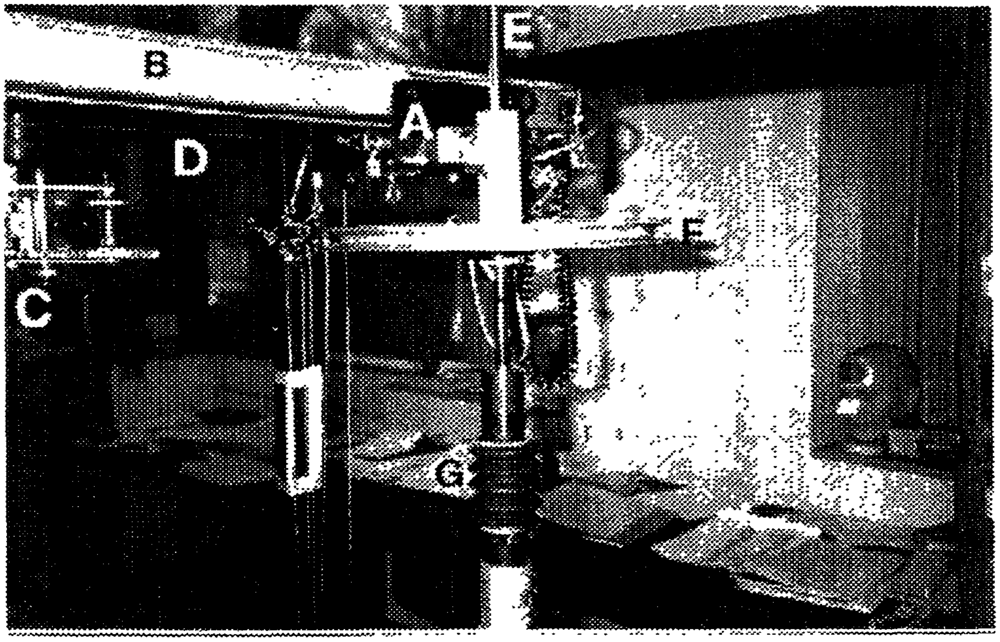


**Figure 3.1-2 Load Transfer Assembly (LTA)**

The load transfer assembly (A) was mounted on an aluminum track (B) with four plastic-coated roller bearings Load was applied by a trailer winch (C) via a stainless cable (D) to the LTA and ultimately to the upper torso It allowed bi-axial rotations and axial translation of the drive shaft (E) in the upper torso Cable force was converted to torque by a pulley (F) and measured directly by a torque transducer (G) which was protected by a plastic bellow.

*Torsional Stiffness*

For the torsional twisting tests, load/torque was applied in the form of a horizontal force acting on a moment arm of 0 14 m. This was achieved by means of a cable wrapped around a 0 27 m diameter pulley on the LTA. A second trailer winch fitted with a potentiometer was used to generate and measure rotation of the upper torso relative to the waist section of the trunk model A strain gauged torsion load cell was installed on the drive shaft to measure pack resistance against such rotations Studies have shown that the average relative angle of twist is approximately 18 degrees full scale which is ±9 degrees about the neutral axis A value of 12 degrees from neutral was used as the maximum for testing Load was applied manually with the trailer winch in a 60 seconds test cycle (25s ramp up, 10s hold, 15s ramp down, and 10s hold) in order to minimize inertial loads from the trunk model Each test included three test cycles before adjustments were made to the setup (straighten clothing, tighten straps, and reposition pack) and testing was repeated to ensure reproducibility.

## 3.2 LC System Component Testing

The LC system component testing jig consisted of a 50th %ile human male mannikin mounted on a rigid support frame (Figure A 7) The mannikin was covered with 5 0 mm Bocklite™ as a human skin substitute. The frame of the component testing jig featured attachment points which allowed for shoulder strap orientations on the mannikin identical to those observed during load carriage In-line strap transducers allowed the tension in the test shoulder straps to be properly adjusted to values typical of users in the field. A series of shoulder straps, varied in shape (straight, contoured) and size (large, small) but identical in material and thickness, were also created for testing on the component jig

Two projects have been completed using the LC system component tester. A Master's thesis investigating the validity of a mathematical model of the shoulder in load carriage involved the placement of one F-Scan™ pressure sensor on the component testing model The accuracy of measurements from the F-Scan™ system when the sensor was adhered to an irregularly shaped surface was then determined Additional investigation looked at the effect of different shoulder strap orientations and the benefit of applying a tangential load lifter strap

The effect of shoulder strap shape was investigated as a final year project, using the LC system component tester instrumented with four adjacent F-Scan™ sensors in the shoulder region of the model Examination of the strap-model interface, as well as the effect of an intermediary layer (combat shirt) on F-Scan™ pressure measurement, was performed.

Future projects are planned for the LC system component tester, including a more complete inspection of shoulder strap styles and their respective contact pressure characteristics, and studies of load carriage system waist belt features

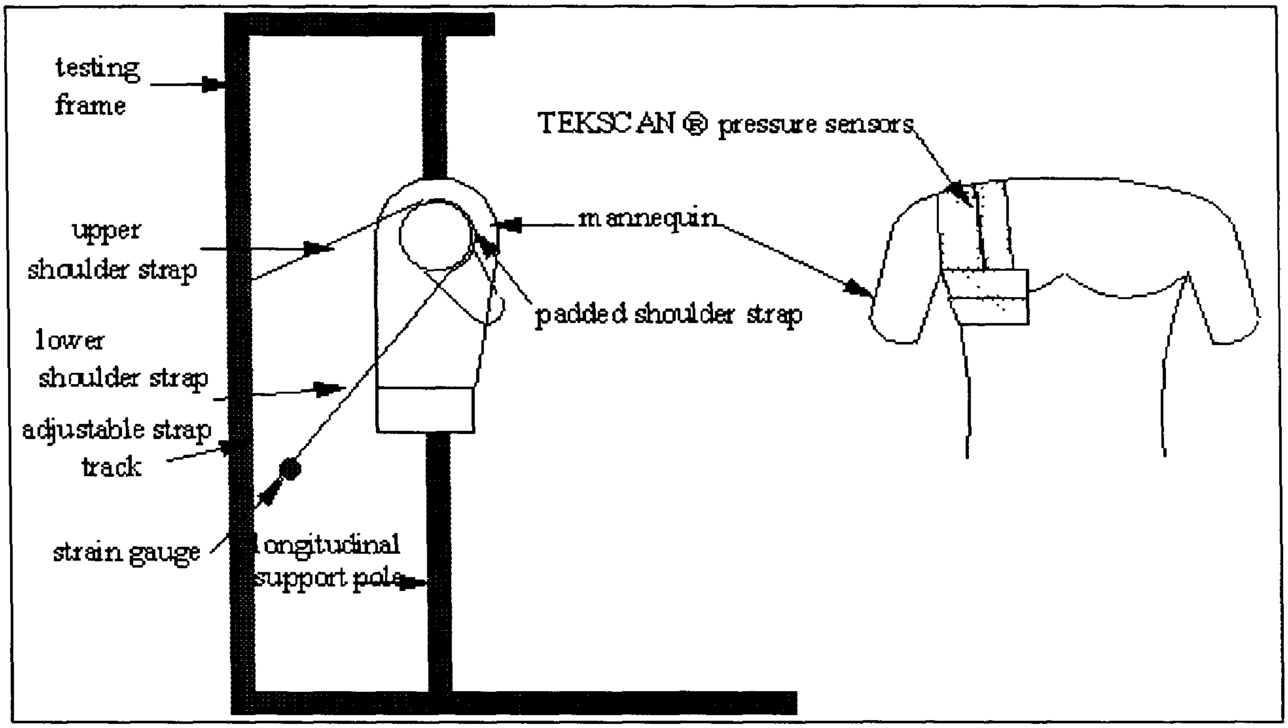


**Figure 3.2** Drawing of LC system component testing jig, with F-Scan™ pressure sensor instrumented shoulder

### 3.3 LC System Portable Testing

This sub-project was an initial attempt to develop a reliable and robust system for measurement of biomechanical and physiological parameters applicable to human testing of advanced personal load carriage systems. The system was designed to test the performance of loaded backpacks when worn by users executing a set of controlled tasks The parameters selected to be evaluated were: contact pressure under one backpack shoulder strap and waistbelt, tensile forces applied to one shoulder strap and waistbelt, skin surface temperature, and heart rate Pressure measurements allow assessment of overall pressure distributions under the shoulder strap and waistbelt, how these distributions vary over time and with the task performed, and where points of unacceptably high pressures are occurring. Strap force measurements are related to friction experienced by the user under the shoulder strap and waistbelt and indicate when excessive strap forces, which can lead to discomfort and possibly minor injury, occur. Skin surface temperature measurement allows a preliminary assessment of the user's ability to dissipate heat which will be affected by the amount of work done by the user, the clothing worn by the user and the environmental temperature Heart rate is indicative of the amount of work done by a user while carrying a load The measured parameters were selected such that data collected using the portable system could be correlated with data collected using the load carriage simulator (LCS)

### 3 3 1 Apparatus

The portable system consisted of two laptop computers, PC#1 and PC#2, and necessary instrumentation for the strap pressure, strap force, skin temperature and heart rate measurements (Figure 3 3-1). PC#1 was dedicated to collection of strap pressure data using the F-Scan™ measurement system and PC#2 was used to collect and store the strap force, skin temperature and heart rate data. The system was set up as follows

*Pressure measurement system*

An F-Scan™ pressure sensor system, which consists of two pressure sensor arrays mounted on flexible plastic, two cuffs which provide signal conditioning and analog-to-digital conversion (ADC) in hardware, and an F-Scan™ PC card and software which accesses and stores pressure array data simultaneously from the two cuffs, was used in the development of the portable LC system testing unit The sensor arrays were mounted on the underside of the right shoulder strap and waistbelt of the LC system. PC#1 was dedicated to pressure data collection. Data can be analyzed using the F-Scan™ software to produce time-varying, two-dimensional displays of the measured data

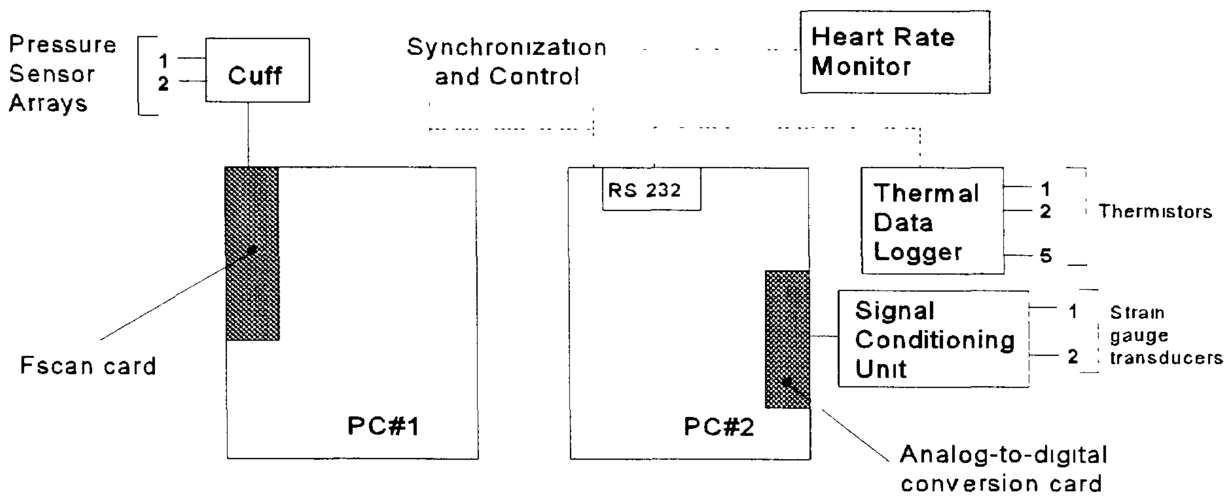


**Figure 3.3-1** Schematic of LC system portable testing unit, with information flow indicated

*Strap force measurement system*

Strap and waistbelt forces were measured using custom strain gauge transducers designed and built for use with the load carriage simulator Two transducers were used one was attached to the outer side of the right shoulder strap and the second was attached to the outer side of the right waistbelt A custom-built battery operated two-channel unit, which provided signal amplification (approximately 3000x), filtering (a low pass filter with corner frequency of 7 Hz) and a regulated power supply for the strain gauge bridge (4 V), was designed and built for use with the portable system. The output of the signal conditioning unit was sampled at 20 Hz using an ADC card installed in PC#2 and stored

*Skin surface temperature measurement system*

Skin surface temperature was measured using five thermistors which were placed at the following measurement sites: chest ($T_{ch}$), front right calf ($T_{cf}$), front right thigh ($T_{th}$), front right forearm ($T_{rf}$) and back left wrist ($T_{lw}$) Following skin preparation to remove hair and prevent sweating, the thermistors were affixed to the skin using Tegaderm™ (3M Industries Incorporated) and then held securely in place with Retelast™ (Nordic Pharmaceuticals Limited), to minimize the possibility that one or more thermistors would lift or move during testing. Temperature measurements at each recording location were logged every eight seconds using a SmartReader™ portable logging unit. Data were subsequently downloaded to PC#2 via the serial port with software provided by the manufacturer Mean skin temperature was then calculated using one of three methods (Burton $MST = 0\ 3T_{ch} + 0\ 4T_{rf} + 0\ 36T_{cf}$. Ramanathan. $MST = 0\ 3T_{ch} + 0\ 3T_{lw} + 0.2T_{th} + 0\ 2T_{cf}$, Newberg / Spealman. $MST = 0\ 34T_{ch} + 0\ 15T_{rf} + 0.33T_{th} + 0\ 18T_{cf}$). The placement of five thermistors allows for some redundancy in the measurement however it should be noted that $T_{ch}$ and $T_{cf}$ are required for mean skin temperature calculation in all three proposed methods In calculating mean skin temperature, preference was given to the methods involving four measurement sites (Ramanathan and Newberg / Spealman)

*Heart rate*

Heart rate was measured using a Polar™ heart rate monitor, worn on the chest, and a logger, worn on the wrist. The heart rate was sampled and stored every 15 seconds. These data were downloaded to PC#2 via the RS232 port with software provided by the manufacturer .

The portable system was designed such that all components are carried by the user. PC#1, PC#2, the TEKSCAN© cuff and the strain gauge signal conditioning unit are carried in the backpack with wire connections to the associated sensors (Figure A 9-2) The heart rate monitor was a self contained unit which was worn on the chest and wrist, and the thermal data logger was carried in a pocket with wire connections to the thermistors. The weight of the equipment carried in the backpack was approximately 10.5 kgs - PC#1 and PC#2 weighed roughly 5 kgs each and the signal conditioning hardware for the pressure and strap force measurements weighed approximately 0 5 kg The weight of the heart rate monitor and SmartReader™ unit was very slight All sensors and instrumentation were positioned for comfort and for minimal interference in the subject's ability to move

3.3 2 System evaluation

The portable field testing system was developed to allow quantified assessment of backpack performance under field conditions, and to measure variables similar to those investigated in LC simulator testing to allow for comparisonof results. This research focus involved assessing the levels of the measured parameters over time and noting changes in the parameters with key body actions The locations of high and average pressure points, alterations in strap forces associated with body motion, and increases in body temperature and heart rate can be determined.

A preliminary test of the system was carried out using one male subject who ran a test circuit which included a sidehill ramp, uphill ramp, and an agility pylon run The subject was videotaped while running the circuit The trial lasted approximately three minutes Pressure under the right shoulder strap and waistbelt, tensile forces on the right shoulder strap and waistbelt, skin surface temperature, and heart rate data were collected continuously during the trial This test was performed solely as a shake down test to bring to light potential problems with the portable test equipment The test data is not reported here due the limited scope and nature of the test

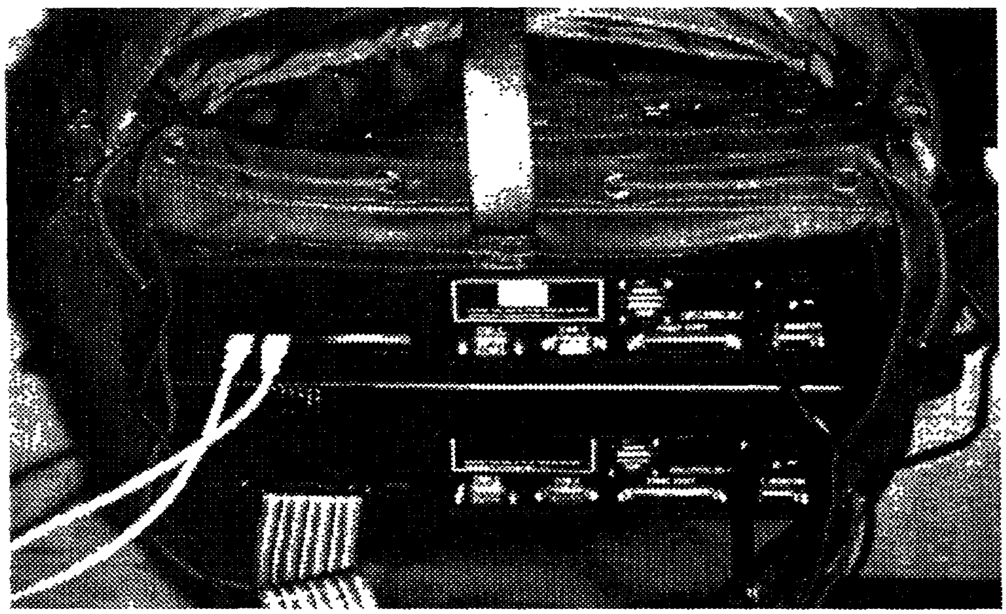

**Figure 3.3-2** Top view of Canadian 1982 Pattern Rucksack with LC system portable testing unit in place

Although the portable system functioned as intended to collect performance data, the following system design problems were identified. The system was designed around collecting data using two portable personal computers (PC's). The F-Scan™ pressure measurement system requires a dedicated PC which necessitated a second PC for collection of strap force data, and for downloading and storage of the temperature and heart rate data. The PC's used were relatively large laptops which provided ISA slots for installation of the F-Scan™ and analog-to-digital convertor (ADC) cards (most laptops and notebook computers have only PCMCIA slots for installation of separate components) Thus the system was large and heavy, filling most of the space in the backpack and weighing approximately 10 5 kgs Although this weight is not excessive, a backpack could not be tested under lighter load conditions Heavier load conditions could be tested by adding weights to the backpack, however the size of the portable system does not allow for testing various packing configurations of normal pack contents As well, in order to synchronize the PC's for the trial, the two mice were fixed to the outside of the backpack with the encoder rollers taped up for an external trigger Although this worked adequately, it is not desirable to carry the mice outside the backpack during a trial as they may get jostled or damaged which may result in an interrupt in the data collection Lastly, the life of the PC batteries during system testing was quite short While this may not be an issue for a single short-duration test, it is a limiting factor in carrying out tests of longer duration.

### 3 3 3 Future directions

The system which has been developed for portable testing of backpack performance has several drawbacks, as noted above, and provides an incomplete picture of how an individual is affected by load carriage. Measurement of a larger number of relevant biomechanical and physiological parameters using a lighter, more compact portable system is essential for proper assessment of an individual's performance while carrying a backpack, with or without other load carriage equipment, and for a comparative analysis of various load carriage system designs

The current system can provide answers to the questions of load transfer and load control (via strap and waist belt pressure and force data), as well as indications of metabolic and performance changes for the wearer (changes heart rate and skin surface temperature) But in order to answer larger questions - e g. how much work is the wearer doing or what are the adverse effects of carrying heavy loads - more information is required Thus, further development of the portable system would include adding other measurement parameters such as activity in relevant muscles (measured as the electromyogram or EMG) and pack-person displacement From the EMG an estimate of the muscular work required to carry the load and an objective measure of muscle fatigue can be obtained Measurement of pack-person displacement would allow for assessment of load shifts with particular actions as well as when a load shift will cause a loss of balance.

A second generation portable system design would be based on a single microprocessor controlled unit for collecting data which would then be downloaded to a PC for analysis The unit would sample and store the desired data - strap pressures and forces, EMG, and pack-person displacement - following signal conditioning (e g amplification). Necessary signal conditioning hardware would be housed within the unit Skin surface temperature and heart rate would still be monitored using the stand-alone devices employed in the current system.

The evaluation trial of the current portable system indicated that it is possible to collect data which is indicative of the performance of a backpack and the individual carrying the pack The proposed changes to the system design would overcome the size and weight problems with the current system and result in a portable system which would give a good overall picture of backpack and wearer performance.

## 4.0 Conclusions and Recommendations

1 Improvements to LC Sim measurement systems and control systems have improved the repeatability and quality of data available LC system testing. Software improvements have also enhanced the testing procedure

2 It is recommended that refinement to LC Sim testing protocol be frozen and results from all systems tested with standardized protocol be grouped in a benchmark data set Future tests should follow current protocol.

3 Development of a portable LCS measurement system should be continued, with increased field work.

4 Pressure calibration improvements should be adopted when possible, either based on in-house testing or results found in new literature A more complete review of alternative pressure measurement systems should also be conducted

## 5.0 References

MacNeil, SK. (1996). Validation and development of a mathematical model of the shoulder for load carriage. *Master's Thesis, Queen's University, Kingston, ON* (Unpublished)

Rose, J , and JG. Gamble. (1994) **Human Walking - 2nd Edition** (Williams and Wilkins, Baltimore, Maryland, USA ) 263 pp

Stevenson, JM , Bryant, JT., dePencier, RD., Pelot, RP., and JG Reid. (1995) Research and Development of an Advanced Personal Load Carriage System. *Report submitted to DCIEM, Contract #W7711-4-7225/01-XSE.*

# Further Developments of
# Comprehensive Load Carriage Measurement System

## Annex A.1

LC Simulator Protocol for Testing

# Protocol for Load Carriage Simulator Testing

1.0 Confirm test protocol and required report format with client.

2.0 Kit Preparation
Purpose: To ready the LC System being evaluated.

2.1 Packing the Payload

2.1.1 The payload consists of 5 x 5 kg steel plates bound together into a lumped mass. A rigid Styrofoam box is built to hold this lumped mass at the centre of the volume of the main LC bag. TheStyrofoamm is glued together to hold the mass in a fixed position within the pack volume. Compression straps are tightened securely to restrain the payload. The resultant mass of the LCS is recorded in Table 2.1

2.2 Location of the Centre of Gravity with respect to the LC System

2.2.1 Position the LC Sim mannikin at 0 degrees forward lead and zero the load cell. Place the LCS to be tested on the LC Sim and tighten the shoulder straps and waist belt to 60 N shoulder and 40 N waistbelt. Record the load cell output for all channels. Measure and record the vertical distance from the load cell neutral axis to the bottom left corner of the LC system (bottom corner of the pack on the wearers left.). Lean the LC Sim mannikin forward until the moment about the lateral axis is zero (My). Record the resultant forward lean angle and the load cell output from all channels. Calculate the resultant position of the centre of gravity (COG) of the payload. Results should be recorded in Table 2.1 in the standard report format.

Figure 2.3 shows the pack fixed origin and axes for C of G measurements.

2.3 Geometric and Mass Properties

2.3.1 Record data required for Table 2.1.

**Table 2.1**(a) Geometric and Mass Properties of Load Carriage System

| LCS Geometric Properties | |
|---|---|
| Length | mm |
| Width | mm |
| Height | mm |
| Delta Z from N/A to pack corner | mm |
| Mass Properties | |
| Mass of LCS Empty | kg |
| Mass of LCS as Tested | kg |
| Centre of Gravity Location (Figure 2.3) | |
| (i) in the anterior/posterior direction | mm |
| (j) in the medial/lateral direction | mm |
| (k) in the superior/inferior direction | mm |

2.4 Placement of Fastrak Sensor

2.4.1 The Fastrak™ sensor is imbedded in Styrofoam block. This block is secured firmly to the payload top on the mid line of the payload, on the edge of the payload adjacent to the back of the wearer (Figure 2 3). Ensure that no relative motion is possible between the payload and the sensor.

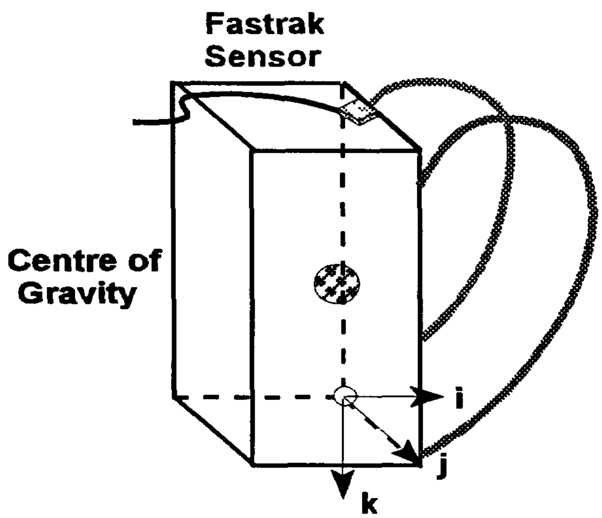


**Figure 2.3** Placement of the Fastrak™ Sensor.

3.0 Strap Transducers

3.1 Examine the physical layout of the LC System to be evaluated and determine the best locations for the strap force transducers. Typically, one shoulder strap will be monitored at the lower pack attachment point and the waist belt transducer will fit just in front of the hip padding. These locations leave the maximums range available for the straps. Transducers require approximately 8-10 cm of clear strapping. Sufficient slack must be maintained in the strap to completely unload it, allowing the transducer to carry the complete load (Figure 3.1). Transducers are sensitive to bending, extreme care must be taken during placement and handling to ensure no bending of the strain gauges occurs.

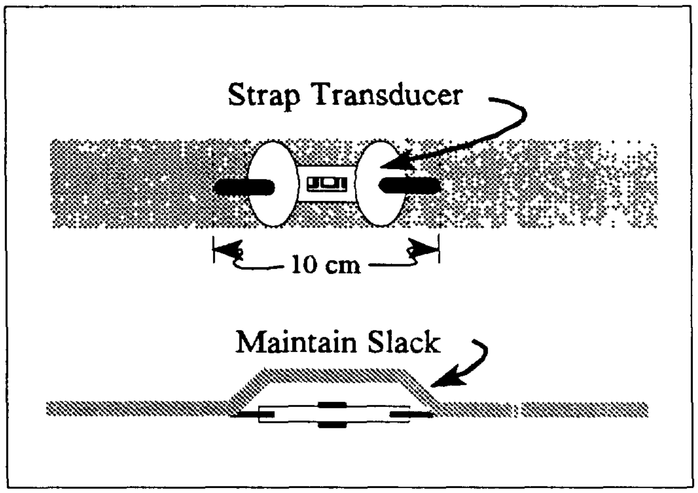


**Figure 3.1** Correct Installation of a Strap Force Transducer

3.2 Place pins through strap, perpendicular to the path of the strap, with gauge hooks held by pins. Always cover pin tips with rubber protectors after placement in straps.

3.3 Stress relieve gauge wires where possible to prevent damage to transducers.

## 4.0 LC Sim Preparation

### 4.1 Hardware

Purpose: prevention of damage to the test equipment and physical setup of LC Sim.

4.1.1 Lubricate face seals on actuators with "Pneu-Lube" pneumatic oil.
4.1.2 Check water trap on pneumatic system, empty if necessary.
4.1.3 Confirm appropriate mannikin body is on LC Sim and check all bolts securing it are firmly tightened.

**Note:** the LC Sim mannikin support is periodically disassembled, the tightness of all bolts on the mannikin body, base pivot, load cell, and mounting plates must be verified before starting the LC Sim. **Failure to do so may result in serious injury**.

### 4.2 Data Collection and Instrumentation

Purpose: ready the system to acquire data.

4.2.1 Begin the laboratory record of test. The Main Lab Notebook is used to record all initial settings, equipment configurations, datafile names, and runtime observations. If it is important enough to write down, even temporarily, it must be written in the Lab Notebook. It forms a complete record of the test history and pages must not be removed from it for any reason. All notations must include some brief explanation of the information being recorded (eg. a heading or title) and be initialed. Additional data may be added by stapling pages into the Notebook, such as a copy of **Table 2.1** *Mass Properties of Load Carriage System* as tested. A subsequent researcher should be able to reconstruct the test history using only the Lab Notebook as a reference.

4.2.2 Assign test ID

Every test configuration is assigned a unique two letter code, this corresponds to a unique physical combination of equipment and kit. This name and a complete description of the LC System setup is recorded in the main lab notebook. All files that form the data set for a LC System evaluation use the following file naming protocol:

*filename.ext* = n1 n1 n3 n4 n5 n6 n7 n8 . m1 m2 m3

Filenames:

n1, n2 = test configuration designation, values A....Z eg. BD
n3 = repeat #, values 1...9
n4 = mannikin id, values F, B, W, P
F=Fred, 95% male, B=Barney, 50% male,
W=Wilma, 50% female, P=Pebbles, 5% female
n5 = test style, values 1,2,...9
Level walk=1, Duck test = 2, Side Slip = 3)
n6 = used to indicate tekscan sensor location, values 1...9
or control run number, values 1...9
n7 = tekscan time, a= 0 min, b=5 min, c=10 min, d=15 min, e=20 min
n8 = tekscan pressure tests, the control run number, values 1...9

Extensions: m1, m2, m3

| | Data files | | Control data files |
|---|---|---|---|
| fsx | Tekscan data file - pressure | ctt | Tekscan control file |
| dis | Fastrak data file - displacement | ctf | Fastrak control file |
| dat | Viewdac data file - load | ctv | Viewdac control file |

### 4.2.3 Fastrak Data Acquisition - Relative Displacement

Software Programs

There are two programs that can be used to collect Fastrak data:

Ftrak2sp.exe and LCSDisp.exe

They are found on the portable computer APLCS#6, path: C:\FASTRAK\

**Ftrak2sp.exe** - records the absolute position of 4 sensors with respect to the source. A single 10 second sample of fastrak data is stored in a discrete output file. Data files are named according to the pattern:

$$\underline{n}_1\ \underline{n}_2\ \underline{n}_3\ \underline{n}_4\ \underline{n}_5\ \underline{n}_6\ .\ \mathrm{dis}$$

where the last character of the filename, $n_6$, denotes the time of the data sample.

| | | |
|---|---|---|
| Sample filenames: | `AX1B1a.dis` | `a = 0 min` |
| | `AX1B1b.dis` | `b = 5 min` |
| | `AX1B1c.dis` | `c = 10 min` |
| | `AX1B1d.dis` | `d = 15 min` |
| | `AX1B1e.dis` | `e = 20 min` |

Raw data is rotated (using a spreadsheet c:\disprot.wk4 on APLCS#2) such that the local Fastrak source coordinate system is coincident with the global axis of the LC Simulator and then input into a spreadsheet (c:\displace.wk4 on APLCS#2) for calculation of the relative motion of the payload with respect to a users body. The source is mounted on the left arm of the manniquin.

Initiate this program by running the batch file: **disp.bat** from either c:\ or c:\fastrak

Note: 4 sensors must be connected to the Fastrak, even if only 1 is used.

**LCSDisp.exe** - records and calculates the change in relative position of two sensors, inputs directly into the APLCS postprocessor to generate Relative Displacement plots and Tables. The source must be positioned such that its' x, y and z axes are aligned with the global X,Y and Z. The source is typically mounted on an overhead bracket that positions the source above the head within 30 cm of the sensors on the payload and manniquin head. The pack sensor position is described previously in 2.4 and is connected to port 4 on the Fastrak. The second sensor is affixed to the manniquin's head and is attached to port 3 on the Fastrak. The program automatically records data upon initialization and at subsequent 5 minute intervals to a total of 5 data sets. A datafile contains a complete 20 minute test, consisting of five sets of fastrak data, each set a 10 second long sample at 55 hz.

The datafile naming protocol for LCSDisp.exe is :

AX1B1.dis - contains data for t = 0, 5, 10, 15 and 20 minutes

Initiate this program by running the batch file: **fastrak.bat** from either c:\ or c:\fastrak on APLCS#6.

4.2.4 Confirmation of Fastrak

Record a sample displacement file to test the Fastrak system communications Edit the dummy file and confirm that non zero data values are being recorded.

4.2.5 Tekscan Data Acquisition - Contact Pressures

Initiate the F-Scan programs on the portable computers, APLCS#4 and APLCS#5, using the F-Scan shortcut icon in Windows 95.
Attach the F-Scan cuffs to the sensors being monitored. The typical set up is:

APLCS#4

| | Sensor Location | |
|---|---|---|
| Window | Typical Setup | Alternate Setup |
| 1 | 1 - Anterior Shoulder | |
| 2 | 3 - Posterior Shoulder Scapula | 11 - Low Posterior Shoulder |

APLCS #5

| | Sensor Location | |
|---|---|---|
| Window | Typical Setup | Alternate Setup |
| 1 | 4 - Upper Lumbar | 7 - Left Hip (Iliac Crest) |
| 2 | 5 - Lower Lumbar | 6 - Right Hip (Iliac Crest) |

4.2.6 Viewdac Data Acquisition - Forces and Moments

Initiate the VIEWDAC data acquisition program on APLCS#2. Using the following series of commands, record the force and moment data from the load cell and the strap forces from the two strap transducers. Note: VIEWDAC must be run in MSDOS mode.

cd \VIEWDAC
VIEWDAC

Using the pull down menus, load and run the sequence file that automatically records 10 second durations at 55 hz at 300 second intervals.

FILE, OPEN, SEQUENCE
DATACQ, SIMREC.SEQ

Using the pull down menus, change the name of the output data file :

| | |
|---|---|
| TASK, STOP | |
| WINDOW, SIMREC.SEQ | *-Double click on the sequence file name to begin editing it.* |
| LOOP1 | *-Double click on "LOOP 1" to begin editing it.* |
| ASCII WRITE 1 | *-Double click on "ASCII WRITE 1" to begin editing it.* |
| *Filename* | *-Change the output filename and revise the descriptor line* |
| OK | *- exit the editing session using the OK button, otherwise the changes will not be applied.* |

WINDOW, PANEL 1 - change back to the display panel

Ensure that the "Start/Stop" toggle button is at stop, otherwise the program will begin to record data at the moment you restart the task. Using the pull down menu, restart the task. The program will wait for the screen toggle switch to be tuned to START before beginning the data acquisition sequence. This switch should be triggered at the same time that displacement, and pressure data are recorded.

TASK, START

**Pausing** To pause the force and moment data acquisition, toggle the START/STOP switch.

**Resuming** To resume, toggle the START/STOP switch. Note: the program will acquire a data set immediately after the switch is move to start. This should be time to coincide with the standard time interval.

4.3 LCS Setup

Purpose: ensure **all** systems ready for a test run.

4.3.1 Position LCS on torso.
Visual inspection is used initally to place pack in a balanced position on mannikin. Consult the manufacturer for the correct fitting procedure for their LCS.

4.3.2 Determine C of G of LCS with respect to hip joint of mannikin.

4.3.3 Measure and record forward lean.

4.3.4 Measure and record initial strap tensions. These must be within the established range (40 N +/- 5 N for waist, 60 N +/- 5N for shoulder).

4.3.5 Initiate Pneumatic control system.
Ensure the exhaust valve is closed and the regulator is set to 50 psi line pressure. Run the control software on APLCS#1, this runs in a Windows 95 DOS session, and can be initiated using the desktop icon "LCSIM TEST". This ia a Quick Basic program.

c:\pdp
run test

Using the pull down menu in "TEST.BAS" , enter RUN

4.3.6 Programming of displacement function.
Using the menu selections, choose the type of motion and set parameters such as frequency and amplitude of the motion.

4.3.7 Tuning of control system.
The gain factors for all control parameters for each cylinder can be set under menu selection: Set Control Parameters. This will need to be done for each new test condition Control parameter settings are saved using the first 5 alphanumerics used for the test series.

Example: n1, n2, n3, n4, n5.set

4.4 Final Systems Check

4 4.1 Fastrak - Datafile name confirmed and Fastrak responding

4.4.2 Tekscan - Datafile name confirmed and Tekscan responding.

4.4.3 Viewdac - Datafile name confirmed for record sequence and responding

## 5.0 Test Sequence

### 5.1 Running

The LC Sim is first started and allowed to go through 20 cycles. Having confirmed the motion is stabe, the record sequence for the Fscan, FASTRAK and Viewdac system are triggered simultaneously. The Tekscan movies files are manually named and saved, then using the Fscan pull down menu, new real time windows are opened.

WINDOW, QUICK OPEN REALTIME

### 5.2 Pausing

When the Hospital air supply pressure begins to approach the regulated line pressure being supplied to the valves, the system must be paused to allow the air pressure to rebuild. Currently, the LC Sim can run continuously for approximately 7 to 8 minutes. Instructions for pausing and resuming the force and moment data acquisition sequence have been described previously in Section 4.2.6 and both the FASTRAK and Fscan systems do not require pausing,

Entering any keystroke in the control computer (APLCS#1) will pause the LC Sim. The number of cycles completed is shown at the bottom of the screen and should be recored in the Main Lab book,

## 6.0 Additional Measures and Required Documentation

### 6.1 Photographs

Photographs of the LCS on the LC Simulator should be taken from the front, side and back to document the test setup.

### 6.2 Strap angles

A plum line with a marked length of 250 mm is suspended from the left shoulder of the mannikin. A photograph showing the bottom corner of the pack, the lower attachment point of the shoulder strap and the mannikins shoulder is taken to record the angle that the strap makes with the long axis of the pack. This information is used as input for the biomechanical model.

7.0 Data Analysis

7.1 Relative Displacement Data

Raw data is rotated (using a LOTUS spreadsheet c:\disprot.wk4 on APLCS#2) such that the local Fastrak source coordinate system is coincident with the global axis of the LC Simulator and then input into a spreadsheet (c:\displace.wk4 on APLCS#2) for calculation of the relative motion of the payload with respect to a users body.

7.2 Pressure Data

Data reduction of the pressure data required hand analysis. Because of the labour intensive nature of this, currently only one representative data set is analysed. Data from time = 600 or 900 seconds is typically chosen as a representative recording. Average and peak pressure, and the contact area is calculated for each of the contact area monitored, using the Graph functions provided by Fscan. A 2D contour pressure plot is made of each contact zone

7.3 Force and Moment Data

Force and moment data files are inputs for the postprocessor APLCS on APLCS#1, the control computer and APLCS#2, the Viewdac computer This postprocessor automatically calculates run summaries showing the average, max, min and Delta force values. It also creates a complete set of run plots that are include as an appendix in the standard LCS report.

8.0 Report Generation

8.1 Report Template

A standard report template has been created that provides the complete LC Sim test protocol, and the interpretation of the results and observations presented. It resides on APLCS#3 at the following location:

C:\ERG_Contracts|\Reports\Standard_forms\stdrep.wpd

**DOCUMENT CONTROL DATA SHEET**

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14. ABSTRACT

(U) Under DCIEM contract #W7711-5-7273/001/TOS, numerous improvements were made to the equipment and protocol for load carriage system testing in the APLCS project. These improvements focused on three areas:

1. Measurement Systems
Ground Reaction Forces and Moments - incorporatin of load cell at torso hip level.
Contact Pressure - measurement from four pressure sites with addition of second F-scan system.
Strap Forces - improved transducer attachment method, increased number of gauges.
Relative Motion - source firmly attached on mannikin, improved software developed.
Data Management Software - data collection and display improvements made to software.

2. Physical Systems
Pneumatic Control System - valves and software improved for better control, increase in programmable motions.
Anthropometric Model Torsos - four mannikins created to compare results across sizes and genders.

3. Test Protocol Changes
Stiffness Testing - improved testing jig, data collection automated.
Component Testing - mannikin created for component testing, custom shoulder straps developed.
Portable Testing - preliminary trials conducted of simultaneous quantitative data collection in field.

The nature of these improvements, along with an explanation of their incorporation into the current LCS testing protocol, are further explained in the following section. Recommendations for future test development work, focussing on the portable system, are also included.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U)